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Outlooks of Nanosensors in Medical and Smart Devices, Agricultural and Food Technology

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Abstract: Nanosensors are medical devices where nanostructures are usually employed to sense the chemicals, gases, bio-representatives, electric fields, light, heat, temperature, pH, humidity, etc., since nanomaterials extensively enhance the compassion of the technique. Nano-biosensors utilize the bio element as an indicative constituent and the electrode as a transducer. Nanostructures are used in the system to bridge the space between the converter and bio receptor at a nanoscale. Several nanostructures like nanoparticles, nanotubes and nanowires, nanofibers, nano-pores, self-adhesive mono layers, and nanocomposites are employed to enhance the efficacy and competence of the biosensor device. Recent developments in nanotechnology further enable this field to prepare cost-effective, rapid, efficient, real-time, portable, robust, and disposable sensors for various applications in many areas, including health care. This article reviews a variety of biosensors and biochips, highlighting the function of nanostructures prepared for medical diagnostics, agriculture, food, energy, innovative packaging, chemicals, and other applications.

Keywords: nanosensor; nano-barcode; electrochemical biosensor; optical biosensor; nanoparticles; e-tongue; e-nose.

1. Introduction

Nanotechnology is a promising research area with tremendous impact and application in various fields. Engineering, Medicine, Environment, and Agriculture [1,2]. Nanomaterials' sizes range from 1–100nm and have excellent surface-to-volume ratio quality with unique chemical, optical, and electrical properties, making them an ideal material for studying pathogens. These properties make them suitable candidates for competent interaction with various biomolecular targets due to their smaller size and fast diffusion rate. Under controlled conditions, it can be synthesized into multiple shapes, such as spheres, rods, wires, plates, and bowl-shaped structures, making them ideal for shape changes or agglomerations that change their physical and chemical properties according to external stimuli [3]. Nanoparticles are classified into the following types: Carbon-based like carbon nanotubes (CNTs), carbon nanofibers (CNFs), semiconductor metal oxide-based like zinc oxide (ZnO), titanium oxide (TiO_2), aluminum oxide (Al_2O_3), polymer, lipid, dendrimers, and composite nanomaterials [4-6]. Various researchers have synthesized different engineered nanoparticles to achieve their desired goal. The flowchart-based example of CNT-based nanosensors for detecting cancer cells is shown in Figure 1. Biosensors are intelligent analyzers consisting of a probe, transducer, and detector with biological components such as DNA, proteins, cells, microorganisms, enzymes, and antibodies that induce signals or outputs. The probe collects signals from the analyte and relays them to the transducer, which measures the changes emanating from biological components and converts them into measurable output. Transducers can consist of electrochemical, bulk, optical, and thermistors. The detector picks up signals from transducers and then sent to microprocessors. Post-amplification signals are analyzed, and data is collected [7]. Biosensors with nanoparticles are known as nano-biosensors/nanosensors.

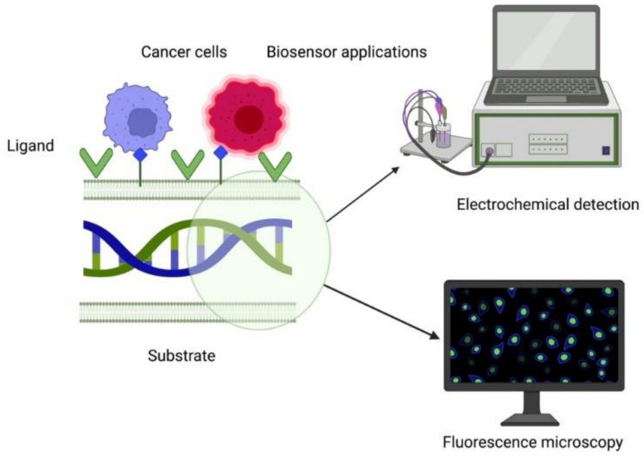

Figure 1. Schematic representation of cancer cell detection via CNT-based electrochemical method.

Nanoparticles increase the competence of biosensors due to the larger reaction surface. Nano-biosensors can be categorized based on means of transmission to generate output, as electrochemical nanosensors depend on nanomaterials or carbon nanotube-based electrodes; optical nanosensors with accredited enhanced optical properties of metallic nanoparticles and quantum dots; Mass nanosensors based on piezoelectric properties of micro-cantilevers and crystals. A schematic representation of a nanowire-based nanosensor is shown in Figure 2.

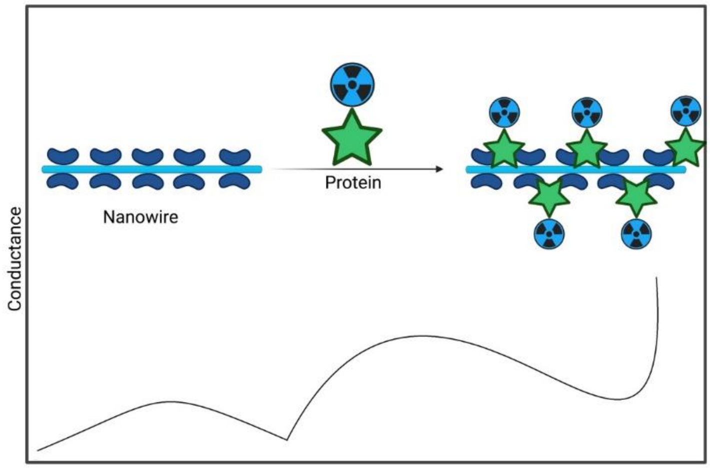

Figure 2. A flow of nanowire-based biosensor conjugated with protein and radioactive ligand.

Nowadays, nanosensors and nano-based elegant delivery systems support farmers in properly using water, nutrients, and agrochemicals to increase crop yield through improved monitoring and minimization of inputs [8-10]. Growing crop diseases and pest problems thus aggravated the situation; the decline in agricultural production has created a global challenge

[11]. It has been estimated that annual losses in the production of crops such as potatoes, corn, peanuts, and soybeans due to pathogen contamination are 10-25% [1,12]. The nanosensor-based approaches might be beneficial for crop improvement and agricultural development.

This article discusses the current understanding of nanosensors applied in various fields, such as electrochemistry, optics, barcode encoding, electronics, agriculture, biomedical, and health care. Furthermore, the review article highlights the importance of nanosensors and various applications reported over the last two decades, as described in Table 1. In addition, we report the significant credentials of the pre-eminent and explain the critical appraisals of nanosensors here.

Table 1. Various types of nanosensors, their characteristics, and applications.

S. No.	Type of Nanosensor	Characteristics	Application	References
1.	Electrochemical nanosensors	Measure chemical reactions between nanomaterial, biomolecule, and bio-element, and target via voltage, current, or impedance		[13]
	a. Amperometry	Measure the current generated during the redox reaction	Detection of organophosphates, sulfonamides, ractopamine & salbutamol, fructose, and hydrogen peroxide ATP sensors: are used for health and diagnostics purposes	[13,15-20]
	b. Voltammetry	Measure changing of potential: Measure redox potential in the electrochemical reaction	- Cyclic Voltammetry Agriculture and food sectors, such as the Detection of carbosulfan in rice, Salmonella typhi, and heavy metal contamination	[21-23]
	c. Potentiometry	Measure the potential between the working electrode and the reference electrode due to ion accumulation	Ion-selective Sensors: for sensing ions: Na^+, K^+, Ca^{2+}, H^+, NH^{4+} in variety of the biological media	[25]
2.	Optical nanosensors	detecting changes in the optical signal	Detection of plant signaling molecules like H_2O_2 and nitric oxide in leaves involved in communication and stress responses through epifluorescence microscopy and sensing of glucose in plants and algae	[27-29]
	a. Fluorescence nanosensors:	Light excites the electron from the ground state and releases a photon	to detect nitrite, reactive oxygen species, pathogenic bacteria, and organophosphate	[30-32]
	b. Quantum dots	Nanocrystals of atoms and semiconductors and it is are based on quantum mechanics principles	Graphene quantum dots: measure soil moisture	[33]
	c. Ratiometric pH sensors	Combination with nanoparticles containing photostable quantum dots and pH-sensitive fluorescent proteins	For detecting pH sensing dyes	[34]
	d. Fluorescence-emitting carbon dots (CD)		To detect metal ions such as Hg^{2+}, K^+, Ag^+ and Fe^{3+} in variety of biological materials	[35]
	e. Carbon point sensor	Quenchers recurring in CDs emit fluorescence in a solution of pesticide, which inhibits enzymatic activity	Detection of pesticides	[36-38]
	f. Surface Plasmon Resonance (SPR)	Metallic, magnetic, and carbon-based nanoparticles, latex, and liposome nanoparticles	To detect concanavalin A, antibiotics, mycotoxins, and pathogens such as *E. coli*	
	g. Herbicide SPR sensor	Combining molecular imprinting into nanofilms and SPR nanosensors	For selective Detection	[39]
3.	Nanobarcodes	Nanoscale constructions are encoded with different coding components, encoding elements having the properties like optical, graphic, magnetic, phase change, etc, and have different shapes and sizes Different coding methods: a. Optical, graphical, and sequence encoding b. Morphological and magnetic encoding c. Phase Change Based Encoding	Multiple applications: -Identification of fish species, bigotry between different meat samples, the study of *Lathyrus clymenum* adulterants, assessment of nematodes in agricultural soils, food pest detection, food and vegetable safety and quality measures -To verify the authenticity of multiple foods	[40-49]

S. No.	Type of Nanosensor	Characteristics	Application	References
4.	Electronic-Nose (e-nose)	It uses artificial neural networks, disease-specific databases, data interpretation software, and disease biomarker detection.	For disease diagnostics and chemical detection of a variety of gaseous mixtures (involving volatile organic compounds). The critical role of the E-Nose in various industries is its use for quality assurance and quality control. Detecting plants and wood and finding redundant pesticides on the leaves of plants. Also used in aerospace, agriculture and forestry Biomedicine, Cosmetics and Pharmacy, Environmental Monitoring, and the Food industry, along with other specific occupations such as biosecurity, disaster management, forensics, army maneuvers	[50-70]
5.	Electronic Tongue (E-Tongue):	Change in electrical properties such as resistance/current when a biomolecule binds to them	Identify five basic tastes: sweet, sour, salty, bitter, and umami taste of multi-component assortments, making it an imaginative tool commonly used in food, environmental and pharmaceutical analysis	[71,72]

2. Electrochemical nanosensors

Electrochemical sensors are based on the theory of electrochemistry and are widely accepted. The electron moment during bio-interstation generates electrochemical signals. Electrochemical nanosensors rely on chemical reactions between nanomaterials, biomolecules, and bio-elements, and they target analytes to generate or absorb electrons and measure them in voltage, current, or impedance [13]. The electrochemical signals generated are quantitatively related to the amount of analyte in the sample. Based on the working mechanism, electrochemical nanosensors can be classified into amperometry, voltammetry, and potentiometry. Amperometric sensors constantly measure the current generated during the redox reaction of an electroactive species, where the potential is set at a constant value, and the current is measured to find out the concentration [13]. After the production of adenosine triphosphate sensors, amperometric nanosensors have been used in health and diagnostics [14]. Amperometric nanosensors have been developed to detect organophosphates, sulfonamides, ractopamine & salbutamol, fructose, and hydrogen peroxide [15-20]. Voltammetry nanosensors measure the current monitored by changing a potential.

Cyclic Voltammetry is usually performed to obtain the redox potential and electrochemical reaction rates generated during the electrochemical reaction with the analyte. A variation of the voltage parameters occurs between the reference and working electrodes by calculating the current between the working and counter electrodes. Thus, the data is plotted as a current versus voltage, which is called a voltammogram. It has a few uses in the Agriculture and food sector, such as detecting carbosulfan in rice, *Salmonella typhi*, and heavy metal contamination [21-24]. Potentiometric sensors are electrochemical sensors where the working electrode's potential is quantified relative to the reference electrode. As equilibrium is reached, the output signal is generated as ions accumulate in the electrolytic electrodes and sensitive field effect transistors. Ion-selective electrodes sense ions such as Na^{+}, K^{+}, Ca^{2+}, H^{+}, and NH^{4+} in various biological media by detecting changes in electrode potential [25]. It has multiple applications to see a variety of analytes, such as preservatives, antibiotics, pesticides, and heavy metals [26]. A flowchart illustration of an electrochemical nanosensor is shown in Figure 3.

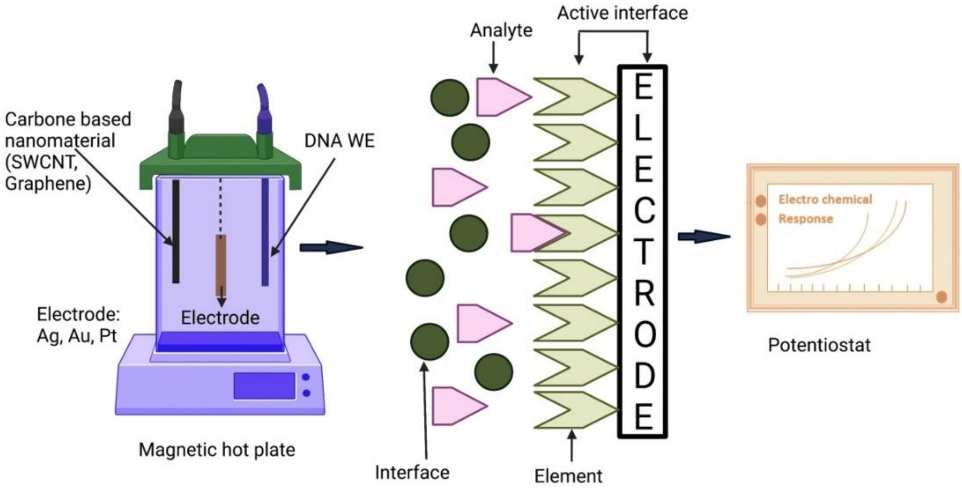

Figure 3. The concept of electrochemical biosensors, an electrode-based biosensor, and its workflow.

3. Optical nanosensors

Optical sensors are based on detecting changes in the optical signal, making them superior to other spectroscopic methods such as absorption, fluorescence, phosphorescence, Raman scattering, and refraction, which see changes in light's wavelength, phase, time, intensity, and polarity. Optical nanosensors have been developed to obtain plant signaling molecules involved in communication and activating stress responses through epifluorescence microscopy of H_2O_2 and nitric oxide in leaves and remote sensing of glucose in plants and algae [27-29]. Luminescence consists of two components: fluorescence and phosphorescence. Ground-state electrons are excited by incident light and produce excited-state excited singlet electrons, which release photons upon return to their ground state. Gold, silver nanoparticles, and quantum dots have natural fluorescence properties, which depend on their morphology and size. Some fluorescence nanosensors have been developed to detect nitrite, reactive oxygen species, pathogenic bacteria, and organophosphates [30-32]. Quantum dots are nanocrystals of atoms and semiconductors with electronic and optical properties based on quantum mechanics. Graphene quantum dots were fabricated as an interdigital electrode with a refractory microsensor to measure soil moisture selectively by interpreting gravimetric moisture as ionic conductivity [33]. Ratiometric pH sensors were developed with nanoparticles containing photostable quantum dots, and pH-sensitive fluorescent proteins showed improved sensitivity and photostability compared to other commonly used pH-sensing dyes [34].

Furthermore, fluorescence-emitting carbon dots (CD) have been synthesized to be used in sensors 30, and these carbon dot-based sensors have been used extensively to detect metal ions such as Hg^{2+}, K^+, Ag^+, and Fe^{3+} [35]. In this way, these sensors are used to see a variety of biological materials. A carbon point sensor was developed to detect pesticides [36]. Pesticides are detected by inhibiting the enzymatic activity of pesticides. Pesticides in solution inhibit enzymatic activity, and quenchers recurring in CDs emit fluorescence [37,38]. Surface Plasmon Resonance (SPR) is an optical sensor that has superior sensitivity and rapid detection. Optimized metallic, magnetic, and carbon-based nanoparticles, latex, and liposome nanoparticles demonstrated an improved SPR detection system to detect concanavalin A, antibiotics, mycotoxins, and pathogens such as *E. coli* [73-75]. By combining molecular imprinting into nanofilms and SPR nanosensors, a herbicide SPR sensor was fabricated as a template molecule for selective detection [39]. Ametryn has been demonstrated through consistent and convenient SPR sensor films using the ATRP method [76]. Surface-enhanced

Raman spectroscopy (SERS) is based on the electromagnetic reaction of light and metal-based nanoparticles that produce enormous enhancements called plasmon resonances. The detection capacity can be increased up to 1011 times to detect antibiotics and pesticides [32,77]. Thiram and methamidophos were quantitatively detected using SERS on the surface of apples [75]. Difenoconazole was quantitatively seen in bok choy by SERS linked to chemometrics [78]. SERS and a rapid pre-treatment method detected trace levels of chlorpyriphos in rice [79]. A sophisticated SERS-based method was developed using silver colloid and pyridine to determine the amount of tricyclazole in rice. Ediphenphos has been detected in rice, thiophanate methyl in peppers, omethoate in peaches, paraquat in fruit peels, and deltamethrin in strawberries using SERS [80-86]. The ability to detect single molecules made the SERS technique very powerful in studying bio-macromolecules to detect and characterize multiple biomolecules in crops [87].

4. Nanobarcodes

Nanobarcodes are nanoscale constructions encoded with different coding components with multiple properties like sizes, shapes, colors, etc. Nanobarcodes have numerous applications due to their advanced properties resulting from their nanoscale length, e.g., higher surface area to volume ratio, exclusive physical and optical assets, and commonly available preparation methods. Some factors should be considered when designing nanobarcodes, such as encoding methods, synthesis tactics, and decoding performance. Encoding elements have optical, graphic, magnetic, and phase modification properties and can convert shapes and sizes [40]. Various coding procedures and decoding techniques are used to produce nanobarcodes, as described in the following subsections.

4.1. Optical, graphical, and sequence encoding.

The optical properties of encoding components are exploited, such as fluorescence spectra, lifetime, and light scattering, and organic dyes, quantum dots, carbon dots, and lanthanide-doped nanocrystals are commonly used for this, and fluorescence microscopy, reflectance spectroscopy, and Raman spectrophotometers are used for decoding. On the other hand, graphical encoding uses optical patterns where the graphics could be in the state of different blueprints created during synthesis. Fluorescence microscopy and optical microscopy are used for decoding. Moreover, sequence encoding uses DNA and peptides as coding components. DNA sequencers and mass spectrophotometry are used for decoding.

4.2. Morphological and magnetic encoding.

It is based on the physical properties of the particles, such as size and shape. Electron microscopy and atomic force microscopy are used for decoding. In comparison, magnetics encoding is based on the magnetic properties of nanoparticles. A vibration sample magnetometer is used for this decoding.

4.3. Phase change-based encoding.

It uses nanoparticles’ solid-to-liquid phase change properties. Differential scanning calorimetry (DSC) and infrared cameras are used for decoding. Many biocide intelligence systems have been developed in the last decade, such as monitoring the physiological situations of Saccharomyces cerevisiae in food and fermentation [88], identifying fish species, bigotry between different meat samples [43], the study of Lathyrusclymenum adulterants [41,42,44], assessment of nematodes in agricultural soils [45], food pest detection [46], food and vegetable safety and quality measures [47-49]. Nanotechnology is essential as metallic and magnetic nanoparticles are widely used to develop improved devices [89]. Gold nanoparticles and iron oxide nanoparticles were individually linked to two different DNA barcodes for fast and robust Detection of *Salmonella enterica serovar enteritidis* in food samples [90]. Recently, exclusive, undetectable barcodes have been created to verify the authenticity of multiple foods [91,92]. The nanobarcodes could be detected using a Raman microscope, appearing as a gold nanodisk array, silver-gold heterodimer nanodisk, or silver nanodisk codes [93]. Nanodisks could be operationalized by complex metal composites, further enhancing their properties. Several reports are on developing nanobarcodes based on fluorescent barcode nanorods, invisible nanobarcodes, and fluorescent DNA dendrimers for product labeling and pathogen detection in food and biosamples [94-97].

5. Electronic-nose (e-nose)

E-nose sensor technologies have rapidly evolved for chemical detection and disease diagnostics over the past decade. With the development of new electronic techniques and related operational methods, there has been extensive growth in E-Nose technology for disease detection and chemical detection of various gaseous mixtures, particularly those involving volatile organic compounds. Advances in sensor techniques, artificial neural networks, disease-specific databases, data interpretation software, and disease biomarker detection have helped improve E-Nose examination methods [50-56,69,98,99]. E-Nose has been used in various sectors such as aerospace [57,58], agriculture and forestry [59,60,66,70], biomedicine [55,56,61,62,64], cosmetics and pharmacy [54], environmental monitoring [63,68,100,101], Food industry along with other specific occupations such as biosecurity, disaster management, forensics, army maneuvers [54,63,67,100]. The most crucial role of the E-Nose in various industries is its use for quality assurance and quality control. E-nose devices are efficient in helping to validate patient identity and confirm the need for irreversible, major medical procedures such as biopsies, organ implants, or prostheses at specific locations [64,65]. A transducer electronically converts the responses from the E-Nose sensor arrays to produce a typical retaliation pattern indicative of the source of the fugitive chemical emissions while being compared to reference databases of identified retaliation patterns from the sample types examined [54,59,102]. E-Nose applications in plant science, forestry, and agriculture have included detecting plants and wood and finding redundant pesticides on the leaves of plants [60,63,67,68,70]. E-nose sensitivity increased accuracy for complex, volatile organic compound (VOC) mixtures, and the lower cost makes them ideal for prior non-invasive disease detection [55,98,103]. Nanostructures such as carbon nanotubes, SiNWs, and platinum nanoparticles have been used in chemo-resistive field effect transistors, which are very effective for determining VOC release from latitudes associated with multiple diseases such as lung, breast, colon, and colon cancer [103]. A flowchart illustration of an E-Nose is shown in Figure 4.

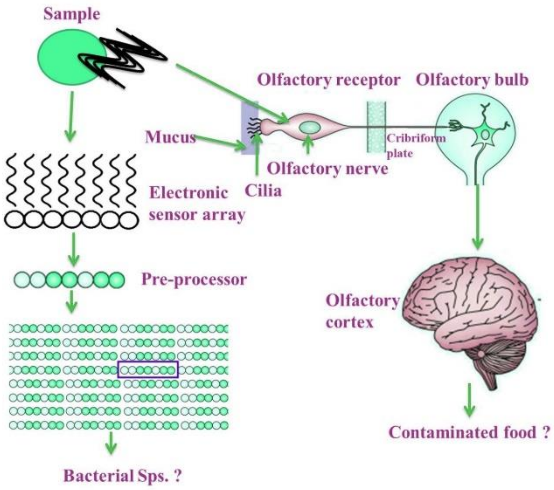

Figure 4. Comparison and parallels of an electronic nose/tongue through olfactory system vs human brain performance.

6. Electronic tongue (e-tongue)

E-tongue tools are nanostructured materials that can change electrical properties, such as resistance/current when a biomolecule binds to them. Several sensors were then prepared to assess and categorize the taste of multi-component assortments [72,99], making it an innovative tool commonly used in food, environmental, and pharmaceutical analysis. The calculated electrical signals are passed through signal distribution algorithms to provide rational results. A range of low-specificity sensors detects analytes despite particular target receptors in this technique, which detect electrical signals to act cross-specific for the current molecules. The earliest prepared e-tongue was used to identify five basic tastes: sweet, sour, salty, bitter, and umami [71]. A wearable e-tongue structure has been developed, focusing on disposable screen-printed electrodes that distinguish between different lager types, predicting their color and alcohol content [104]. Total phenolic content along with identified specific classes are frequently analyzed characteristics, as phenols strongly associate properties such as color, astringency, bitterness, and stabilizer in the aging process of wine, so many bioelectronic tongues have been projected for quantitative analyses of phenolic content [105,106]. A similar procedure was also used for beer to assess flavonoid content [107]. An electronic tongue with microfluidic impedance was prepared for gliadin detection [108]. It could distinguish gluten-free products from products intentionally mixed with traces of gluten by detecting gliadin levels as low as 0.005mg/kg. An electronic tongue based on metal oxyhydroxide/multiwalled CNT-modified electrodes for easy analysis of carbohydrates while optimizing the production process. It is essential to quantify the galactose, glucose, xylose, and mannose content in sugar cane bagasse for treatment with appropriate microorganisms to produce second-generation ethanol [109]. E-Tongue has been effectively used to study the number of organophosphate pesticides at low nanomolar concentrations [110]. A potentiometric E-tongue composed of cross-sensitive lipid membranes was used to discriminate between 34 water samples counting still, dazzling, and essential mineral water. pH and conductivity were also calculated quantitatively [111].

Sensors for estimating API flavor have been continuously prepared. A potentiometric sensor array was used to affect common drugs such as ibuprofen and roxithromycin and showed that microencapsulation exerts the same taste-masking effect on both salts [112]. The most recent e-tongue development is the real-time hemodialysis process study [113].

Disposable implantable solid-state ion-selective electrodes were developed for investigating endoscopic examinations [114,115]. The disposable screen-printing E-Tongue could measure chloride in sweat to detect cystic fibrosis, mainly affecting the lungs, pancreas, liver, kidneys, and intestines [116]. Ischemia could be seen in gastric tissue using a tiny and mass-producible pH K+ sensor by endoscopy using an E-Tongue System [114,115]. A flowchart illustration of an E-tongue is shown in Figure 4.

7. Precision agriculture

Precision farming includes information technology utilizing the management of profitable farming with the highly desirable goal of increasing the overall goal of expanded crop production while decreasing the use of fertilizers, pesticides, herbicides, etc., by controlling environmental fluctuations using speckled tasks to be tracked. The global position system, geographical information system, and remote sensing technologies make farming more efficient and less expensive. Local environmental conditions are measured using geographical information system techniques to identify the nature and location of crop expansion disturbances that could control pathogens and apply site-specific fertilizers, critical for yield studies, pest monitoring, parameter measurements such as drought and flooding, and forecasting [117]. Variable rate technology (VRT) and yield monitors are the essential components for precision farming, where they combine with a geographical information system and global position system. VRT is a precise tool that influences the inconsistency alerts and uses the inputs focused on crop needs, using consolidated results for the analysis of soil quality and crop development, fertilizers, chemicals, and water needs, which subsequently delivers and reduces the increased yields its input costs, in this way, it reduces waste and labor costs. Nanotechnology enables this setup to increase the acceptance of autonomous nanosensors linked to the global position system array to provide adequate screening services for plant prosperity and soil health [8-10,117]. Illustration nanosensors used in the agricultural and food sectors are shown in Figure 5. It has been suggested that microorganisms in the rhizosphere of wheat or other crops interact with roots, creating a chemical signaling network that forms the basis for releasing plant or microbial metabolites into the soil [118]. Based on this impression, intelligent nano-fertilizer delivery platforms for micronutrients such as Zn and Fe have been developed. Smart nano-fertilizers have been suggested to be fitted with nano-biosensors in a bio-polymer, covering a coating on all sides of the fertilizer parts. Nanotechnologists have developed a system to study the regulation of plant phytohormones, which are responsible for root extension and seedling arrangement and react with auxin, helping researchers figure out how plant roots adapt to their environment [119]. Using microelectronic circuitry, nanotechnology-based microelectromechanical system sensors (MEMS) can sense and respond to environmental switches. A schematic representation of a MEMS-based nanosensor is shown in Figure 6. A sensor formulated on acetylcholinesterase attachment on multiwalled CNT modified the fused film deprivation electrode to detect organophosphorus pesticides and saw the presence of paraoxon at the part per billion level [120]. Nano Smart Dust, including tiny wireless transponders and gas sensors, could reduce the intensity of environmental pollutants [121]. Innovative nanosensors have also been developed to monitor the temperature of a single cell effectively [122].

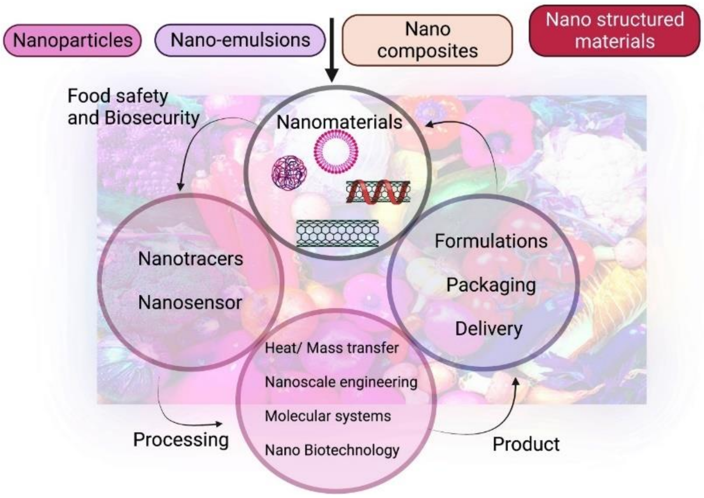

Figure 5. Various applications of nanoparticle-based nanosensors in agriculture and food.

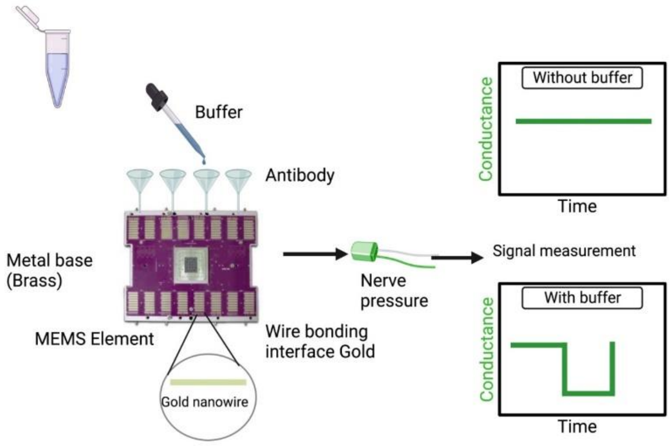

Figure 6. Various applications of MEMS-based nanosensors in the field of drug targeting and delivery.

8. Biosensors-on-chip

The microfluidic biosensors (lab-on-a-chip) platform provides robust and inexpensive diagnostic tools developed by integrating microfluidics and sensor technology. It allows for combining chemical and biological components in a single step, providing the latest technology for sensor devices such as wearable and disposable, simultaneous detection, improved accuracy, and real-time analysis of different analytes in a single tool [123,124]. Nucleic acids (cDNAs) present in adequate amounts in the blood of cancer patients were detected using this technique [125-127].

9. Conclusions

Nanotechnology is an emerging field that can be helpful in the development of tools for applications in agriculture, environment, energy, food, drug delivery, medical devices, biosensors, diagnostics, electronics, etc. Electrochemical sensors have problems with temperature and pH and are also stubborn. FRET nanosensors have issues related to statistics when examining complex data. Various nanobarcodes based on fluorescence, fluorescent DNA dendrimer, and undetectable nanobarcodes have been developed for product labeling and pathogen detection. Various nanobarcodes have been developed based on different nanostructures for monitoring the physiological status of microorganisms in the food and fermentation industries, bigotry between different meat samples, Detection of fish species, food and vegetable safety and quality measures, Detection of foodborne insect pests, evaluation of nematodes in agricultural soil. E-Nose technology was developed for disease and chemical detection of various gas mixtures. These are very helpful in identifying the patients and assisting in lengthy medical processes, biopsies, organ implants, etc., and can benefit the industry for quality assurance and quality control system development. In plant science, it is beneficial for wood-detecting pesticide residues in foliage. The E-Tongue technique is helpful in the categorization and perception of flavors of multi-component assortments, making it an innovative tool commonly used in food, environmental, and pharmaceutical analysis. The broad applications of nanosensors in agriculture include the delivery of pesticides and herbicides rationally coated with nanomaterials, delayed and balanced release of nutrients, and gene transfers. Nanosensors also play an essential role in precision agriculture. It can be used to determine nutrients and measure moisture, temperature, pH, disease diagnostics, and physiological states of plants to help maximize crop yield and minimize input costs. Geographic information system technology and nanosensors play a crucial role in discovering the local glitches to monitor plant pathogens, soil conditions, drought, floods, and weather forecasts. The nanosensors market is growing day-to-day and is expected to reach $1,321.30 million by 2026. Around 20,000 researchers and 2,000 employees are involved in the area. Integrating microfluidics and nanosensor technology provided a platform for developing real-time, wearable, cost-effective, single-use devices for various applications in developing nanosensors in different sectors. Aside from having multiple advantages, some issues are associated with nano biosensors, such as standardization, validation, device cost, and potential environmental toxicity, which need to be evaluated. Formulating piezoelectric nanosensors is costly and labor-intensive. The synthesis and characterization of nanoparticles are also expensive and require attention. Overall, progress in nanosensing promises a brighter future for this field in various sectors.

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Conflict of interest

All the authors declare no conflict of interest in this manuscript.

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